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## **Failure Analysis of a Cracked CH-47 Swashplate Rotating Ring, S/N BCW-1379**

**by Scott Grendahl and Russell Yocum**

ARL-TR-3826

June 2006

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# **Army Research Laboratory**

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## 1. Introduction

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The U.S. Aviation and Missile Command (AMCOM) sent the U.S. Army Research Laboratory's (ARL's) Weapons and Materials Research Directorate (WMRD) three swashplate rotating rings (S/Ns BCW-828, BCW-1379, and W1718240-1) from the CH-47 helicopter for investigation. The components were examined due to the presence of cracks found during routine overhaul. These cracks were on and adjacent to the bearing retention shoulder. One of these rotating rings, S/N BCW-1379, was included for a detailed failure analysis to determine the cause of the cracking. This component was QDR exhibit number W45N7V-04-0307. The components were required to be forged from aluminum alloy 2014-T6. The focus of this investigation, BCW-1379, was characterized by nondestructive inspection, chemical analysis, optical microscopy, scanning electron microscopy (SEM), and mechanical testing. The holes of the rotating ring were numbered 0–36 around the perimeter, consistent with the convention of the MELRs from Boeing helicopters. Figure 1 depicts the as-received BCW-1379 rotating ring from Corpus Christi Army Depot, TX. Additional investigators from Boeing, Mr. Kirk Grassett, and from AMCOM, Mr. Gary Wechsler, took part in the investigation at ARL-WMRD.

The objective of this work was to determine the root cause of the cracking associated with the bearing retention shoulder on the CH-47 swashplate rotating ring BCW-1379.

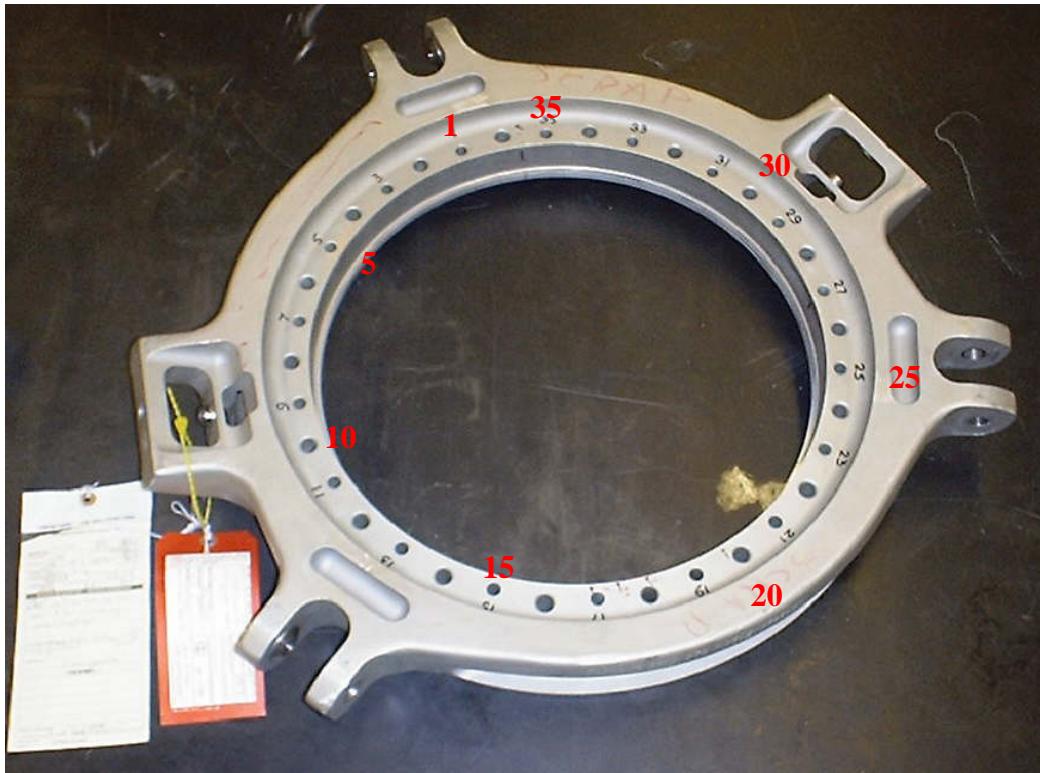


Figure 1. As-received component BCW-1379 swashplate rotating ring.

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## 2. Fluorescent Penetrant Inspection

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The bearing retention shoulder of BCW-1379 was inspected utilizing Magnaflux ZL-37, fluorescent, post emulsifiable hydrophilic with a 4.0 level sensitivity penetrant in an attempt to detect the indications that had been previously noted by other investigators and any other possible indications. Two crack indications were observed. A circumferential crack was observed near hole 5 measuring approximately 0.35 inches in length. The crack was located approximately 0.015 in from the 16.19-in inner diameter (ID) bore. This indication can be observed under white light in figure 2 and in black light in figure 3. Additionally, an indication was observed near hole 30. This indication appeared to be related to a raised fretted area. The crack is depicted under black light in figure 4. This crack measured approximately 0.035 in on the shoulder face and 0.005 in onto the 16.19-in-diameter surface. Two areas of corrosive attack were also revealed near hole 30. However, there were no cracks associated with these attacked areas. One of the two areas with corrosive attack is shown in figure 5 under white light and in figure 6 under black light.

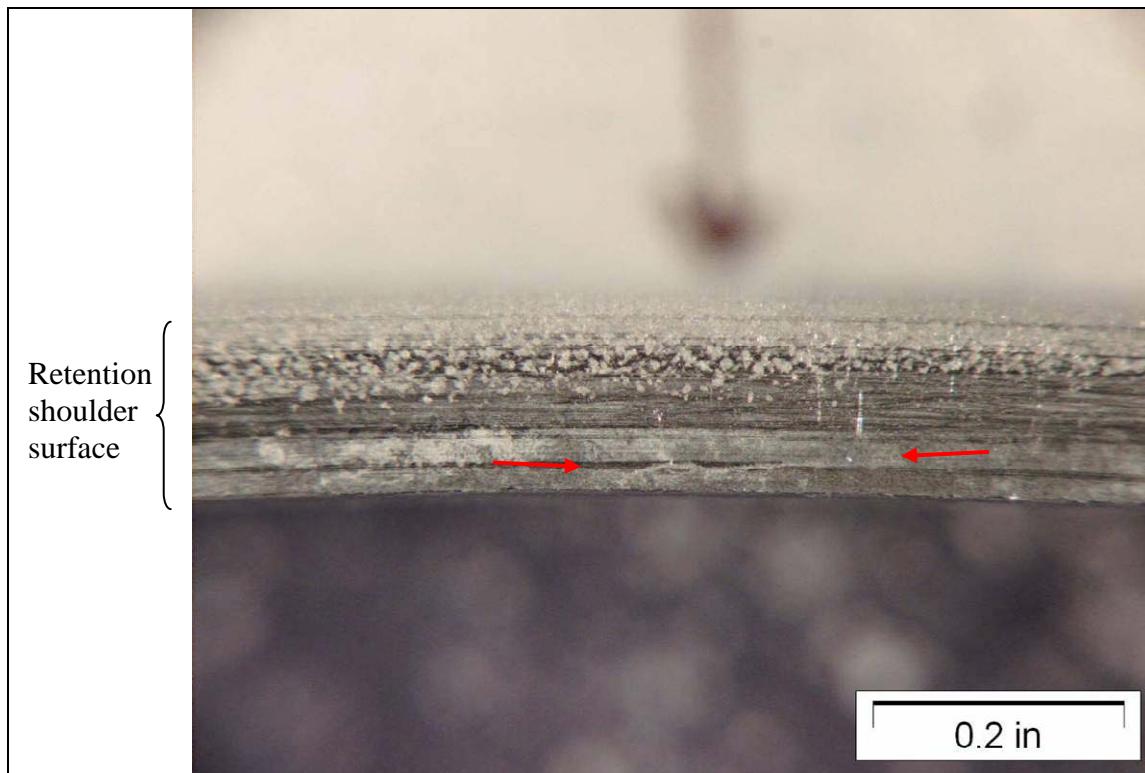


Figure 2. White light indication of the circumferential crack at hole 5.

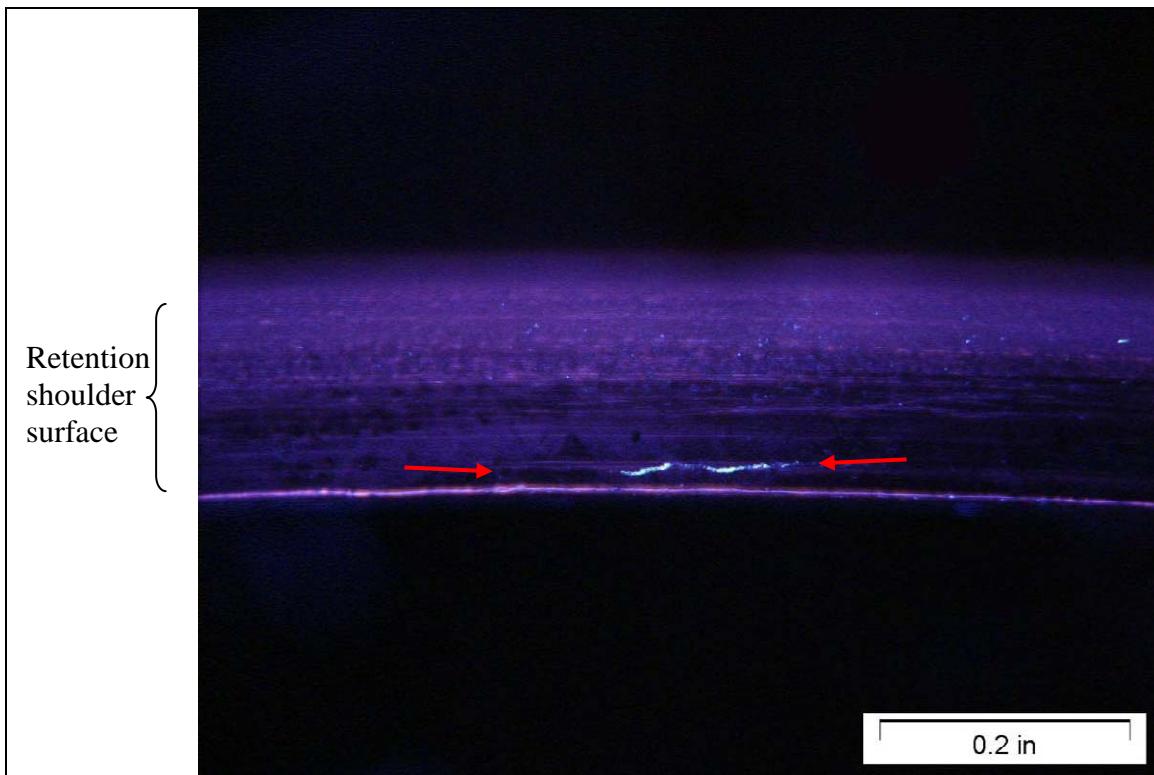


Figure 3. Black light indication of the circumferential crack at hole 5.

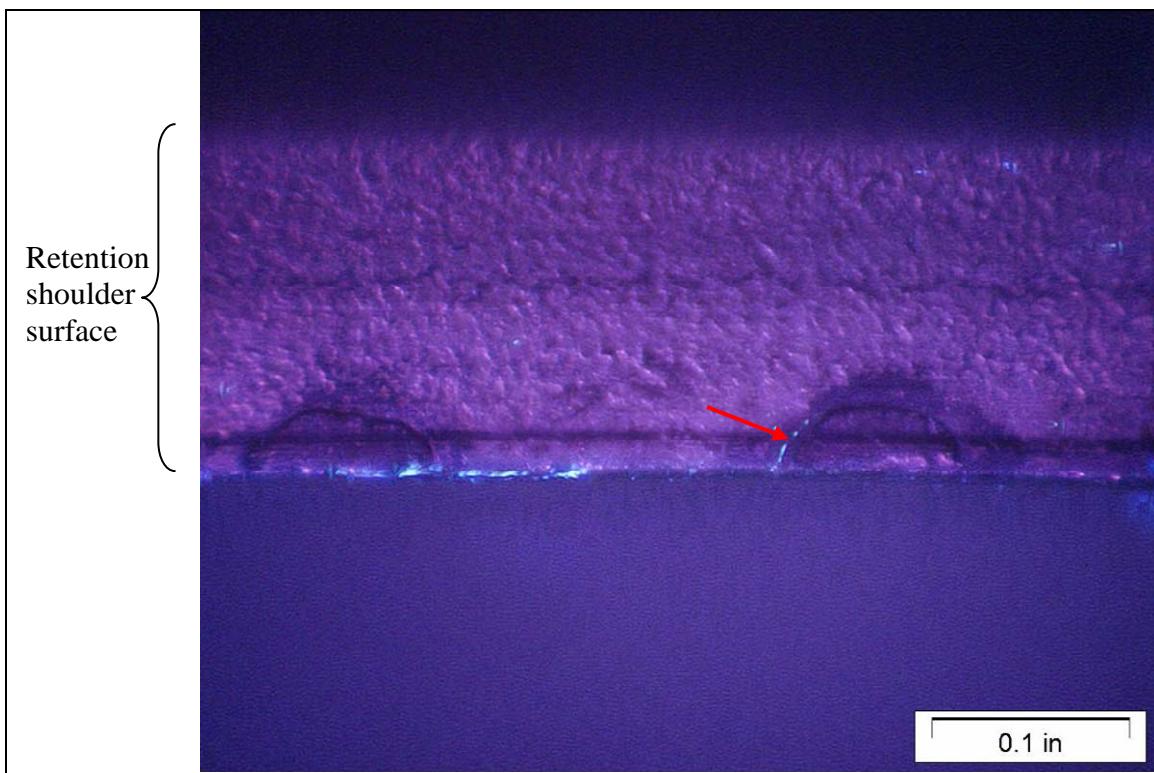


Figure 4. Black light indication of the crack at the thumbnail fretted area at hole 30.

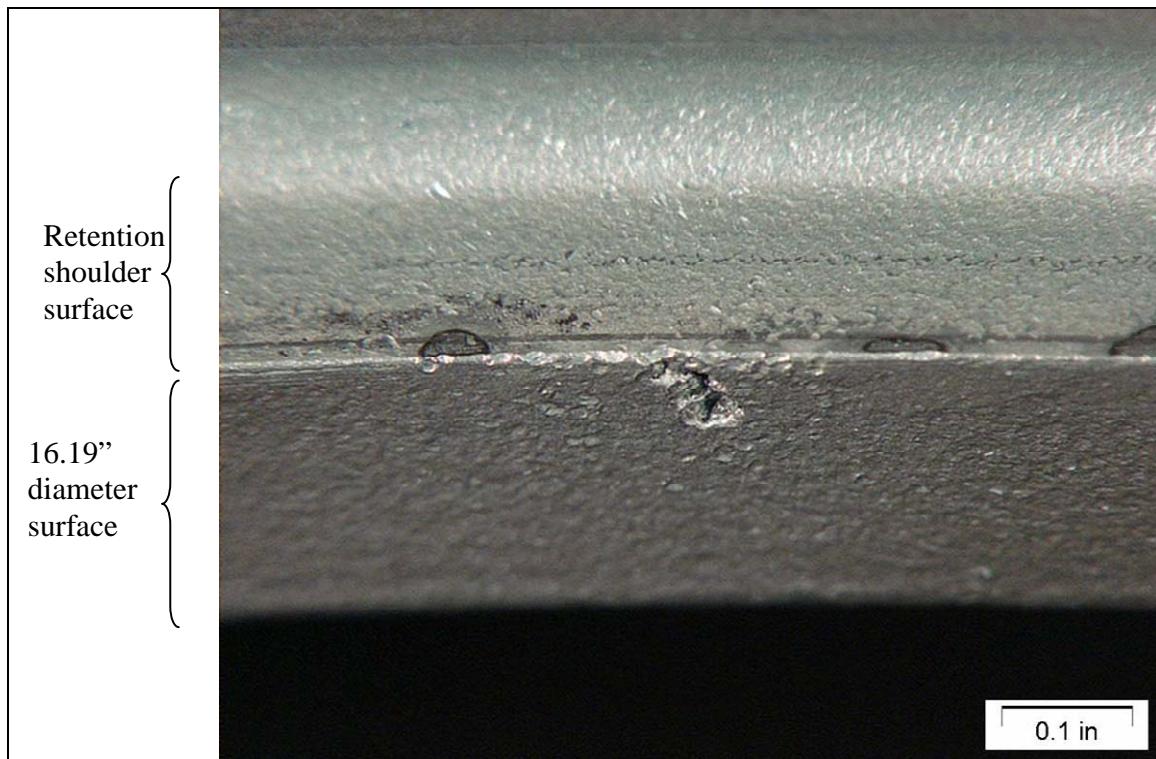


Figure 5. White light macrograph of the corrosive attack near hole 30.

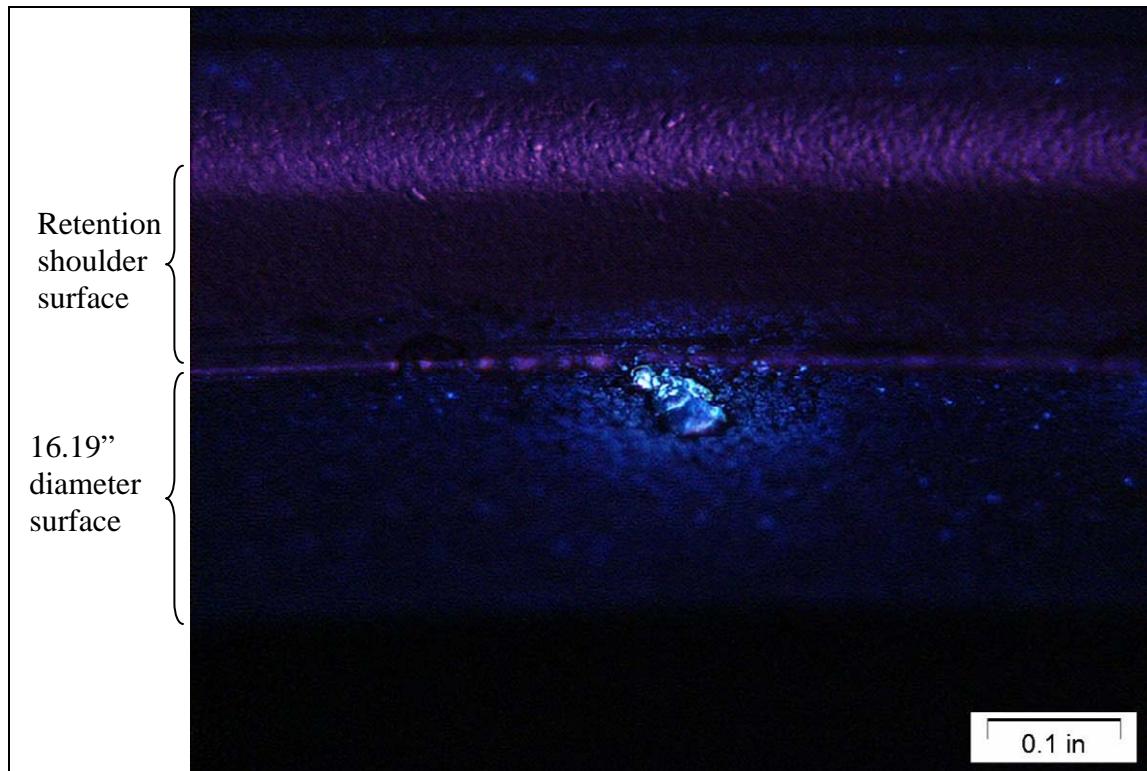


Figure 6. Black light macrograph of the corrosive attack near hole 30.

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### 3. Visual Inspection and Light Optical Microscopy

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The bearing retention shoulders of all three rings were inspected visually and with light optical microscopy. For ring BCW-1379, cracks and crack measurements were verified at hole 5 and hole 30. The bearing shoulder wear pattern appeared discontinuous, with the most severe wear occurring between pitch link locations. At all other locations, the shot peening impressions appeared uniform and continuous. The discontinuous wear step was caused from contact with the swashplate bearing and the contact loads between the two components. The other two rings had a much more severe, continuous wear step around the bearing retention shoulder.

Differences in the severity of the wear step were most likely due to the loads applied to the components, slight differences in dimension, and time in service coupled with the service conditions. Although the wear step on BCW-1379 appeared less severe than the wear step observed on the other two rings, examples of similar damage mechanisms were apparent.

Significantly fretted areas were observed at holes 3–4, 6, 9, 15–17, 26, 27, 32, and 35. An example of a significantly fretted area is depicted in figure 7. Raised areas where damage on the 16.19 in diameter caused material to be pushed up on the bearing retention shoulder could be observed at holes 9, 11, 13, 16, 20, 23, 30, and 34. These raised areas only had considerable fretting at holes 20, 30, and 34; however, the raised areas at hole 30 can be observed in figures 8 and 16. The damage to the 16.19-in-diameter surface is highlighted for clarity in figure 9. Compare figure 9 with figure 8. The damage at the left in both photos is the most obvious.

The crack at hole 5 was atypical of the previous cracking observed on other rotating rings. There was no apparent fretting wear in the area. There did exist, however, a circumferential score line that ran along the path where the crack initiated. This score line extended approximately 3 in along the circumference in this area and is clearly visible in figures 2, 9, and 10. A similar score line was apparent at other locations around the circumference of the bearing retention shoulder surface. It appeared to be an impression left by the edge of the outer race of the mating bearing and the contact loading between the components. Although the bearing that mated with this rotating ring was not available for inspection, the team examined a similar bearing from another rotating ring. This “representative” bearing exhibited raised machining marks on the edges of the inner and outer races of the bearing. The crack at hole 5 was circumferential, approximately 0.35 in long, and only 0.015 in from the 16.19-in-diameter surface. It initiated and propagated circumferentially (see figures 10 and 11). The circumferential cracks observed on other rotating rings initiated near the outer edge of the wear step (approximately 0.90 in away from the 16.19-in-diameter surface) and quickly turned radially in favor of the service stresses on the component. To determine if the crack was the edge of a machining burr rolled over by subsequent shot peening, a section was made through one end of the crack and examined metallographically. Figure 12 shows the resulting cross section clearly indicating that the crack

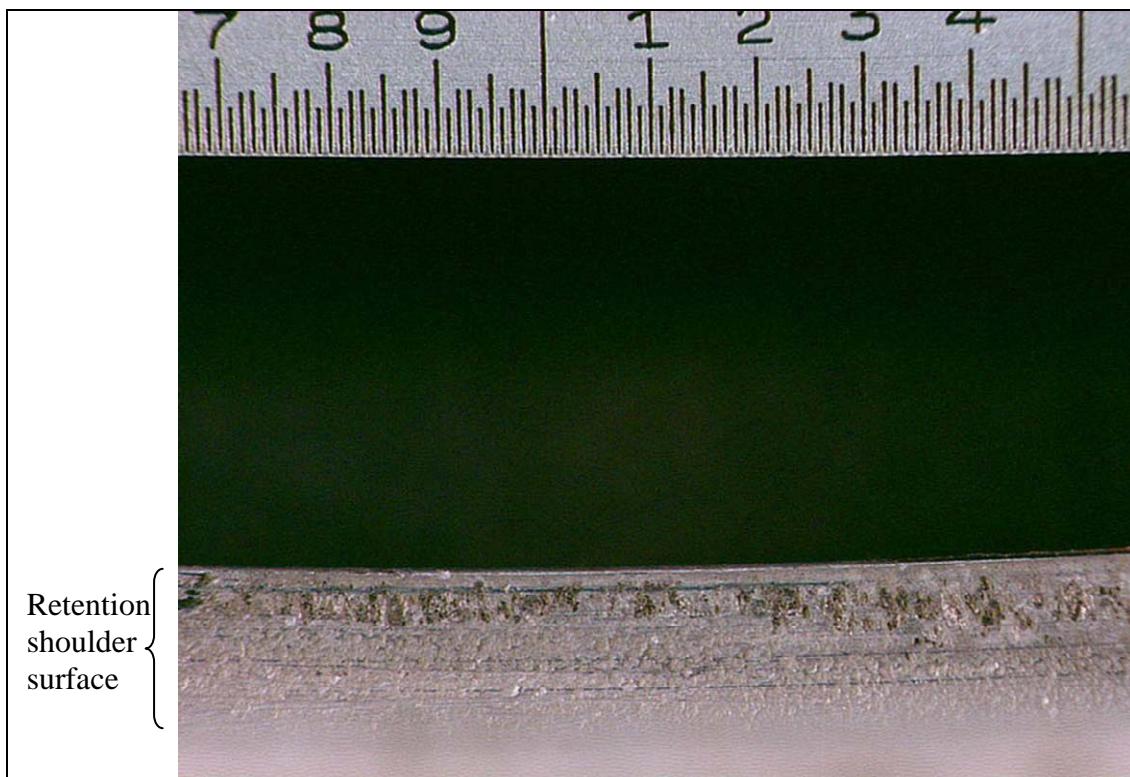


Figure 7. Typical fretted area on the bearing retention shoulder (hole 9).

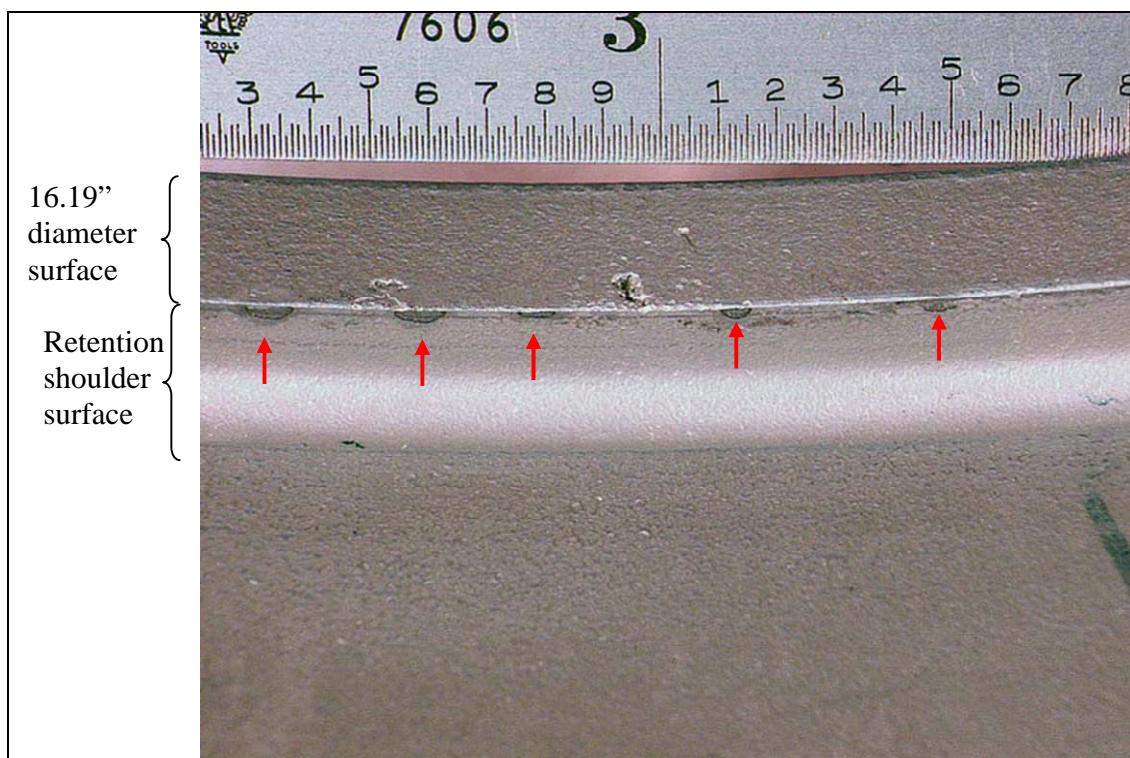


Figure 8. Typical raised fretted areas associated with 16.19-in surface damage (hole 30).

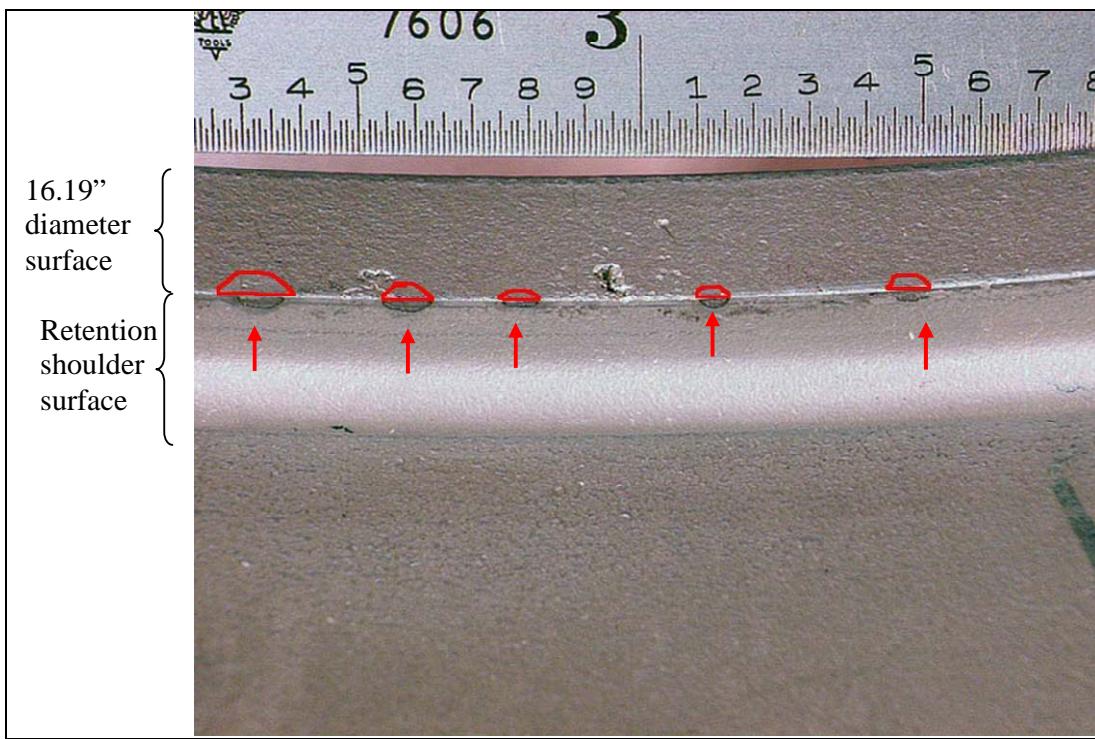


Figure 9. The damage causing the raised fretted areas associated with 16.19-in surface.

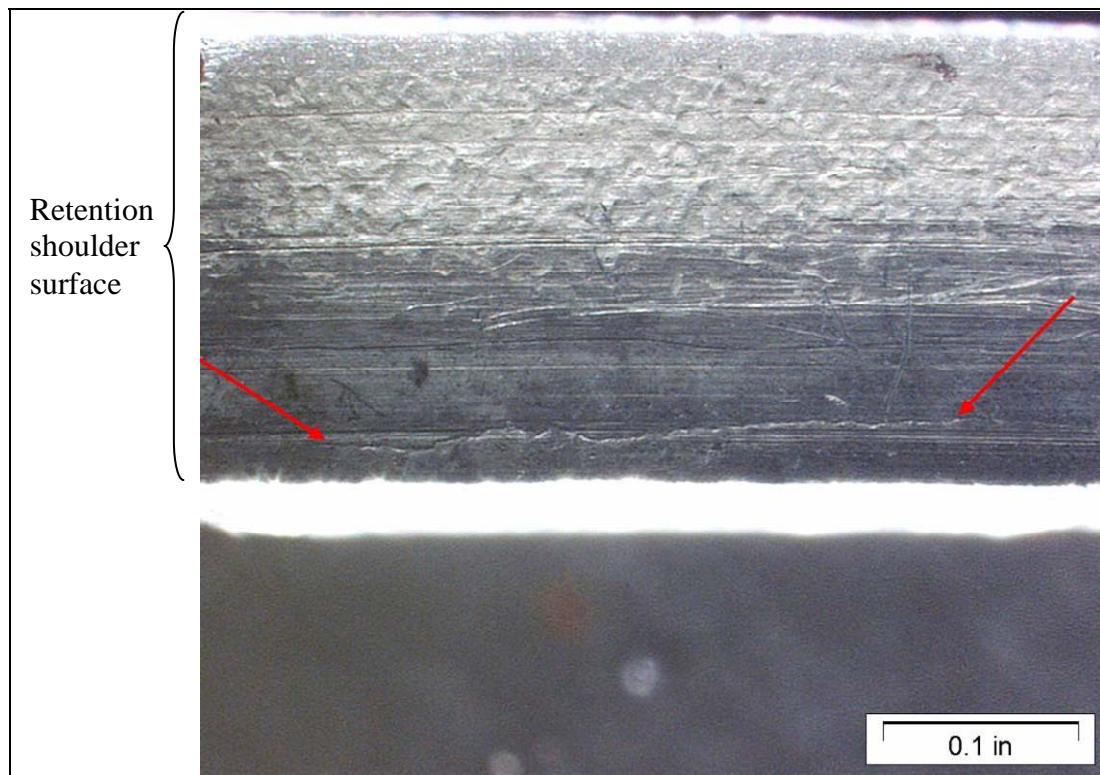


Figure 10. Photograph 1 of the circumferential crack at hole 5.

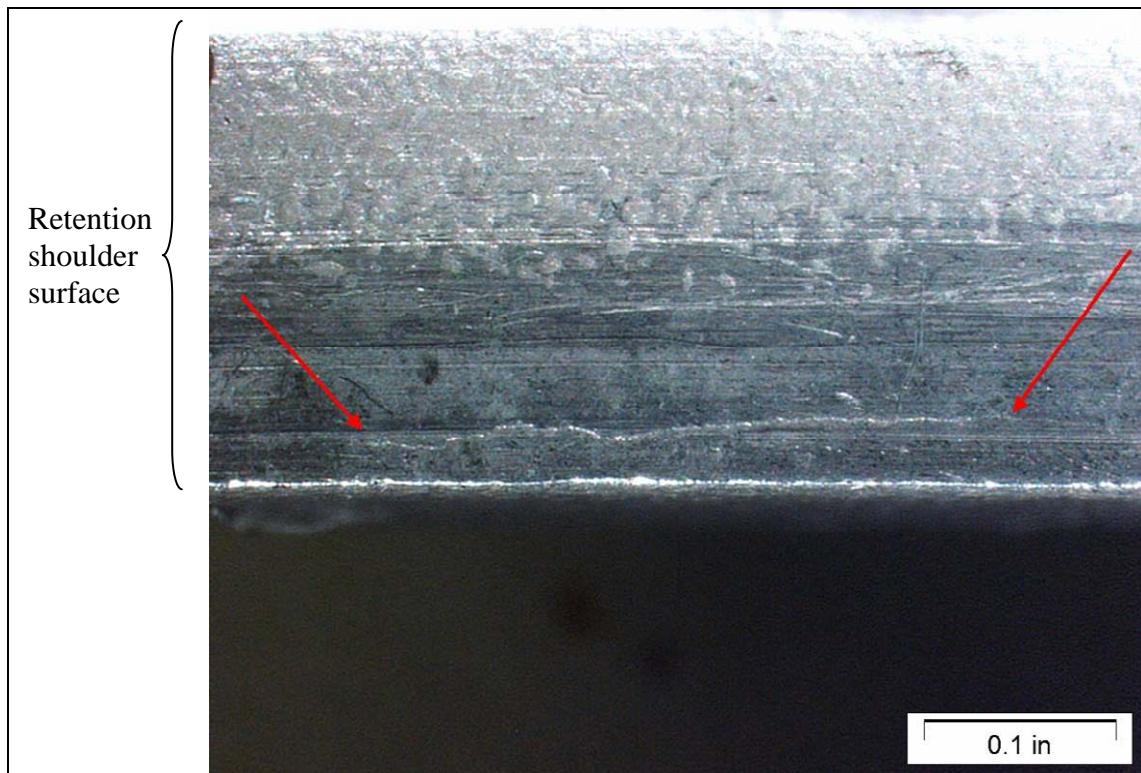


Figure 11. Photograph 2 of the circumferential crack at hole 5.

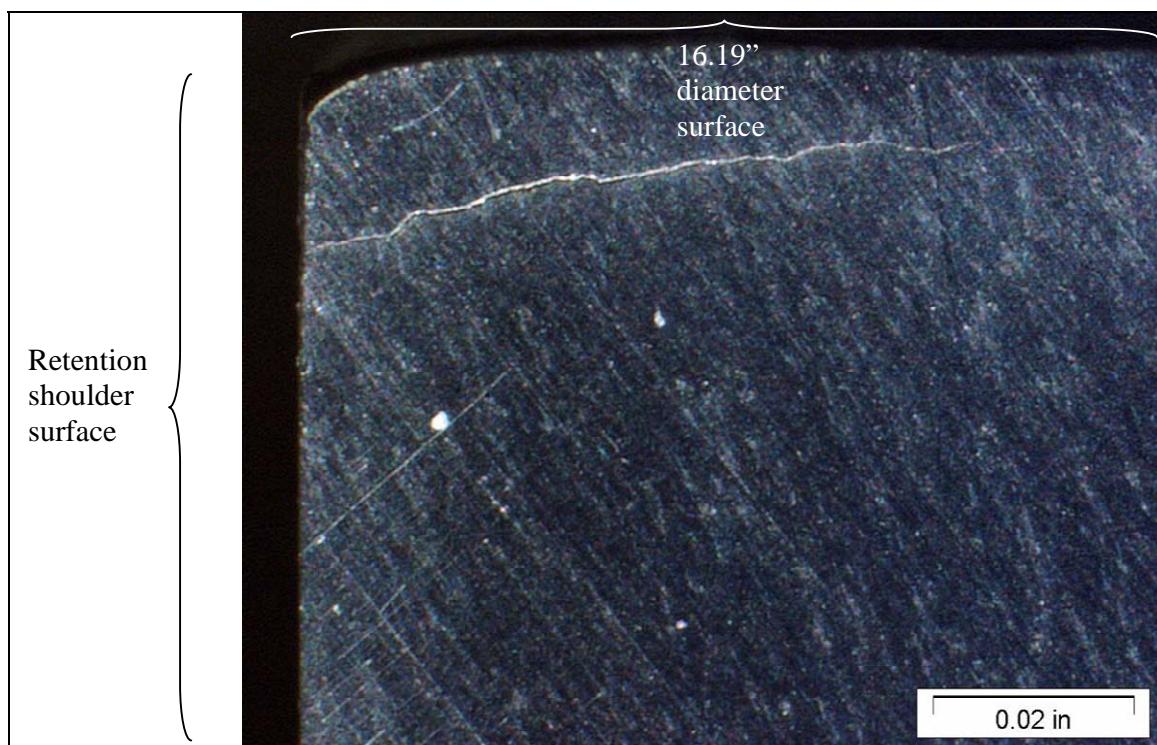


Figure 12. Cross section of the crack at hole 5.

had considerable depth and was not simply a rolled-over burr. It can also be seen in this figure that the crack roughly paralleled the 16.19-in-diameter surface and would have likely propagated considerably farther in both the axial and circumferential directions before contacting the exterior surface of the component. The crack was then opened for fractographic examination.

Examination of the crack's fracture surface revealed at least three origins, all initiated by fatigue on the bearing retention shoulder surface. The beach marks and radial lines suggested it was unlikely that more origins existed within the material consumed during metallographic preparation, prior to the crack being opened (observable in figures 13 and 14). The crack propagated by fatigue from these three origins to a total depth of 0.090 in and a total estimated length of 0.350 in. Figures 13 and 14 depict the fracture surface with red arrows and lines indicating the crack origins and propagation fronts, respectively. A black product was visible on approximately half of the fracture surface; this product was analyzed with Energy Dispersive Spectroscopy (EDS) (and discussed within the SEM section of this report). The depth of the wear step at hole 5 was approximately 0.001 in. No mechanical damage was noted on the 16.19-in-diameter surface in the area of the crack and no other anomalies were observed in this area.

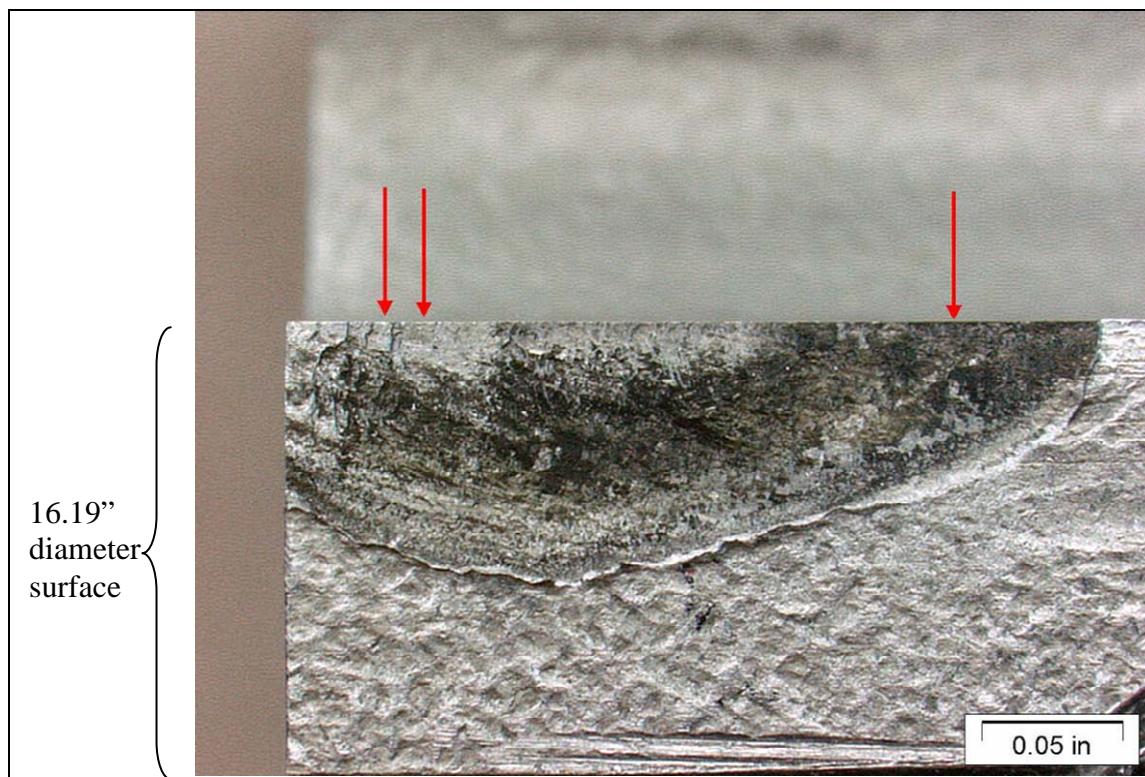


Figure 13. Fractograph of the opened crack at hole 5 (arrows indicate origins).

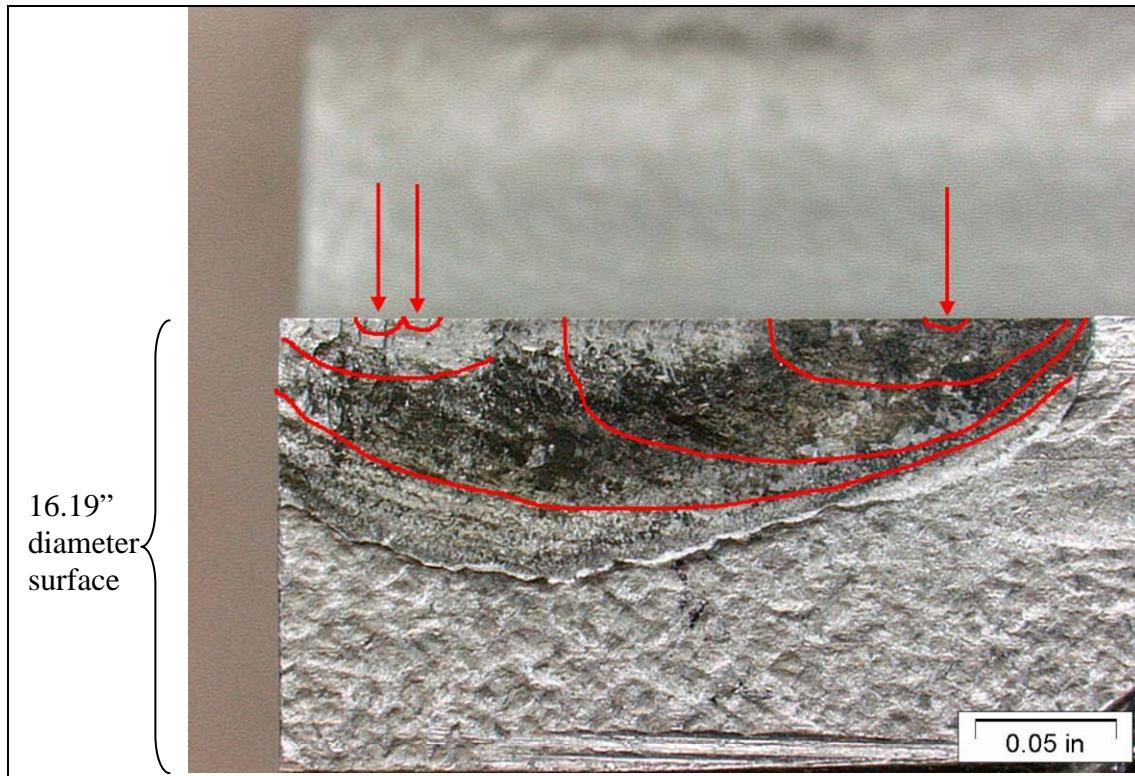


Figure 14. Fractograph of the opened crack at hole 5 with propagation lines.

The crack at hole 30 was similar to some of the cracks observed on the other rotating rings. This crack formed at the edge of a raised fretted thumbnail induced by damage incident to the 16.19-in-diameter surface from an unknown source. This crack can be observed in figures 4 and 15. The crack was very small, measuring approximately 0.035 in long  $\times$  0.005 in deep. Due to its small size and apparent similarity with the cracks on the other rotating rings previously examined, no attempt was made to open this crack for fractographic examination. It was assumed that this crack initiated and propagated by fatigue as a result of localized high stresses due to the effect of the raised thumbnail on the load distribution between the rotating ring and the bearing. Pitting corrosion was observed at two locations in this area as well as of the 16.19-in-diameter surface. The pitting corrosion can be observed in figure 16 along with the raised fretted thumbnails. There were no cracks associated with the pitting sites. It is not believed that they are associated with the damage incident to the 16.19-in-diameter surface.

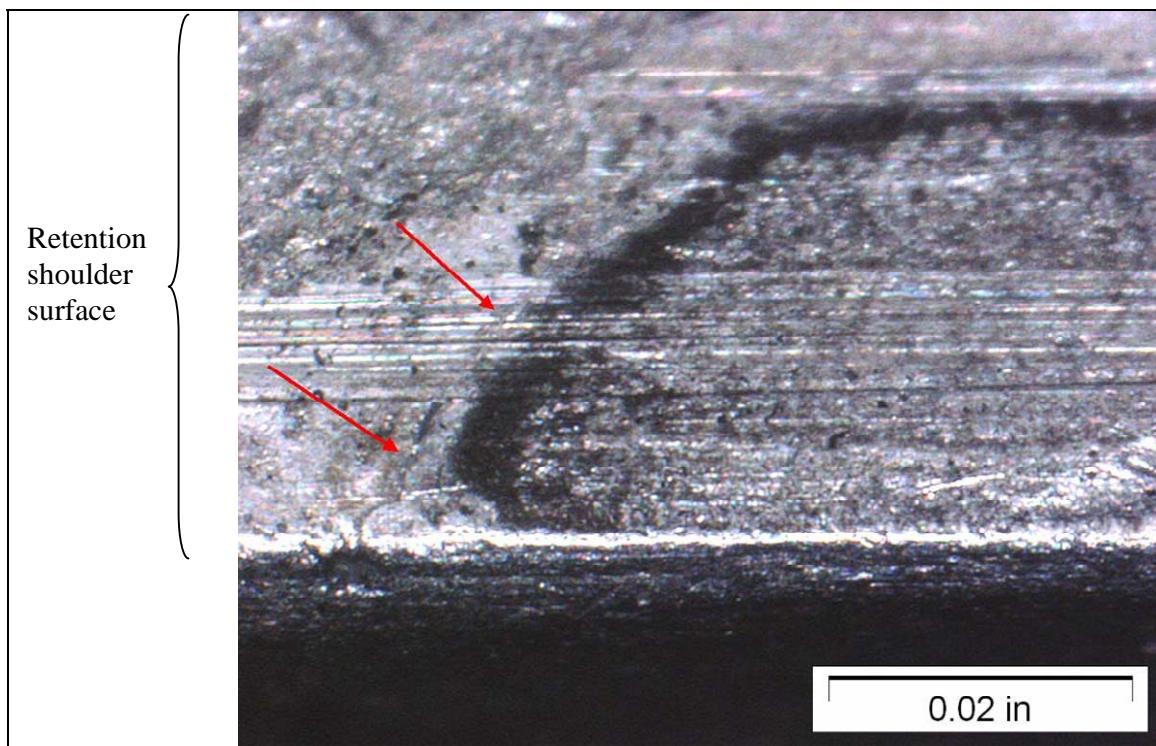


Figure 15. Crack at a raised fretting site located at hole 30.

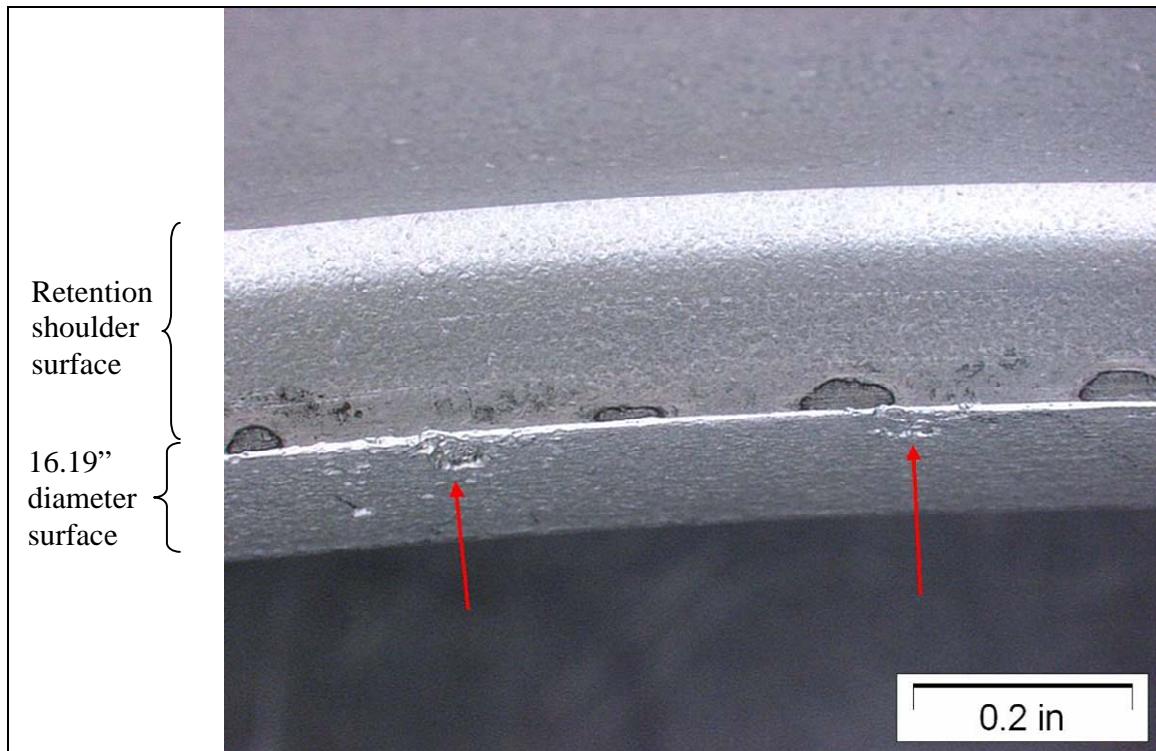


Figure 16. Corrosion pits and raised fretted areas at hole 30.

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#### 4. Scanning Electron Microscopy

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SEM utilizing a JEOL-JSM 6460-LV was performed to investigate the fracture surfaces in greater detail. The crack at hole 5 is depicted in the electron fractograph in figure 17. At closer inspection, evidence of cyclic fatigue crack propagation was present (figure 18). The fracture morphology was transgranular throughout the cracked region. EDS was utilized to analyze a dark product on the fracture surface. The product appeared to have high peaks for oxygen and aluminum, indicative of oxidized aluminum and that this crack either took a long time to form or formed quite a while ago. No more specific information about the age of the crack could be determined. This spectrum can be observed in figure 19. Aside from the wear step and the score line previously described, there was no significant mechanical damage or corrosion present at the origins.

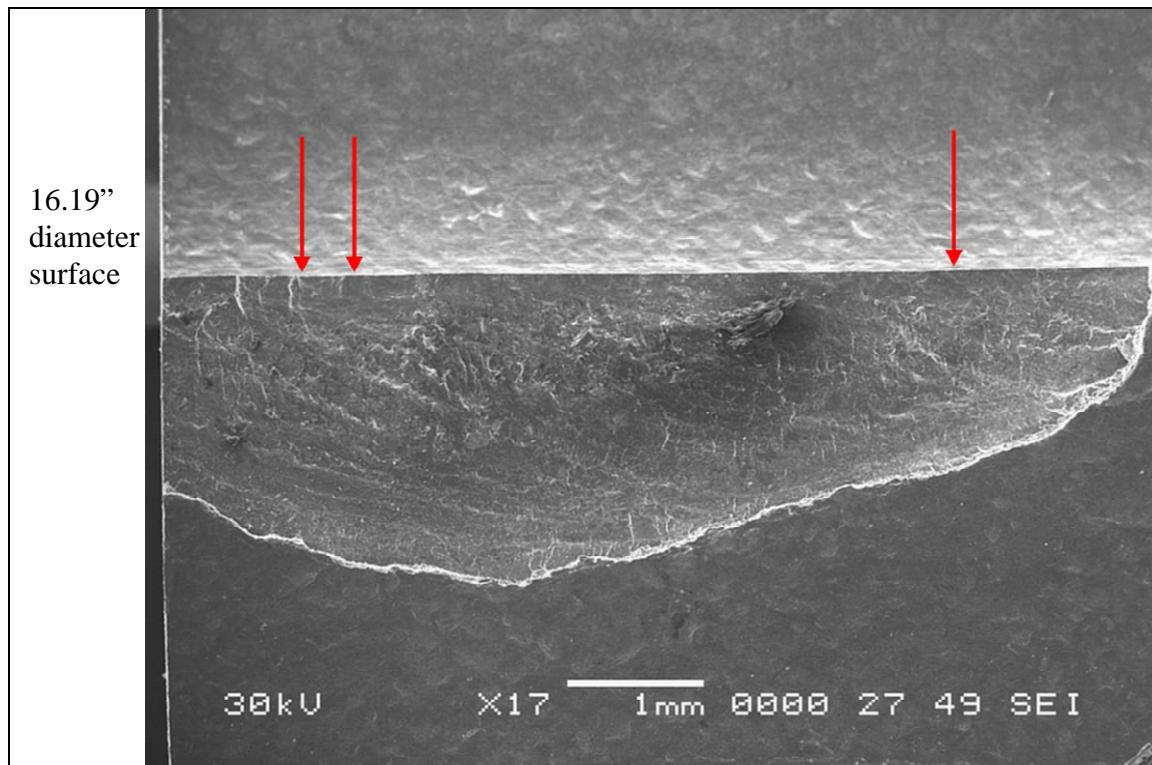


Figure 17. SEM fractograph of the crack at hole 5.

The crack at hole 30 was also inspected with electron microscopy. A raised area (approximately 0.002 in high) was fretted and a crack initiated along one side of this fretting site. The raised area was very similar to other raised thumbnails previously discussed. The crack observed at this location was very similar to the cracks investigated by Boeing on the other rotating rings (raised thumbnails with associated cracks were common on BCW-828). It appeared that mechanical

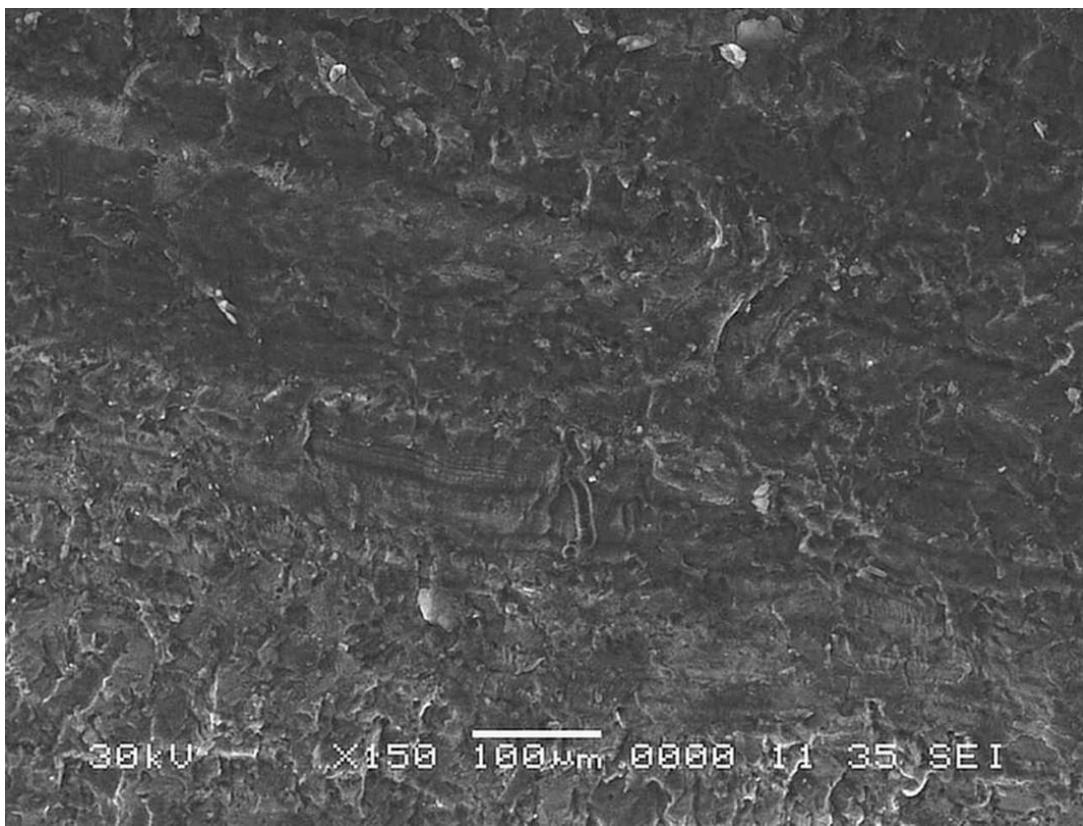


Figure 18. SEM micrograph depicting cyclic crack propagation at hole 5.

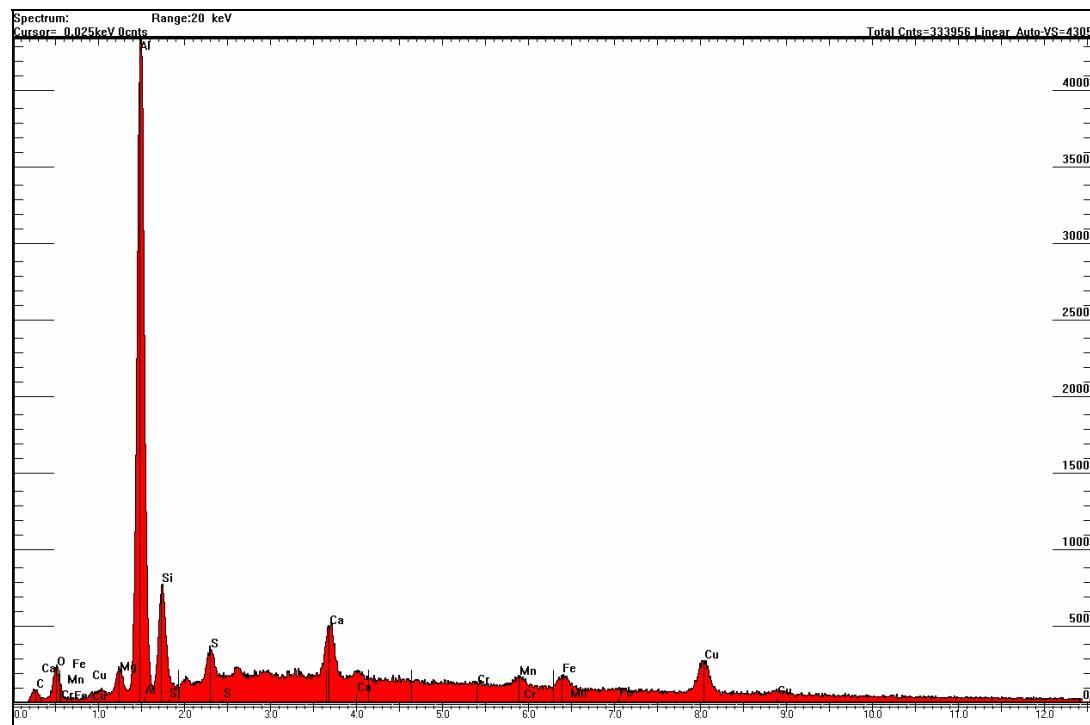


Figure 19. EDS spectrum from the black product on the fracture surface at hole 5.

damage on the 16.19-in-diameter surface caused these raised thumbnails. The mechanical damage was likely from a blunt hard instrument as the shot peening impressions were not completely marred by the damage. It was apparent that the raised areas were preventing normal load distribution along the bearing retention surface, as there was little disturbance of the surrounding shot peening impressions signifying reduced or no contact with the mating bearing. As previously mentioned, no attempt was made to open this crack due to its small size and similarity with other cracks associated with raised fretted sites examined on other rings. No other significant wear or corrosion (other than that previously described) was observed in the area. The SEM examination was limited to the cracked areas on the bearing retention shoulder.

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## 5. Metallography

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A radial cross section was prepared through the bearing retention shoulder. The section was ground and polished through  $0.025\text{-}\mu\text{m}$  noncolloidal silica. Subsequently, the specimen was etched with Keller's reagent. The microstructure of the rotating ring material was found to be consistent with 2014-T6 aluminum. The depth of the wear step was believed to be at its maximum in this cross section and measured approximately 0.001 in. The onset of strain hardening of the material below the wear can be observed as a light etching effect. The microstructure beneath the wear step can be observed in figure 20. The typical microstructure of the base material is depicted in figure 21. No other abnormalities were observed. A radial cross section was also evaluated for the grain flow induced by forging. The section was polished and macro-etched with NaOH. Forging flow lines were observed generally following the contours of the component, confirming that the component was forged as required by the engineering drawing. The grain flow pattern is shown in figure 22.

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## 6. Chemical Analysis

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The chemical composition of BCW-1379 was analyzed with direct current plasma emission spectroscopy (DC plasma). The sample was sectioned from an area adjacent to hole 5 where the circumferential crack was located. The results are listed in table 1 along with the chemical composition requirements for AMS-QQ-A-367 as specified by the engineering drawing. The chemical constituency of the component compared favorably with the requirements.



Figure 20. Microstructure near the wear step.

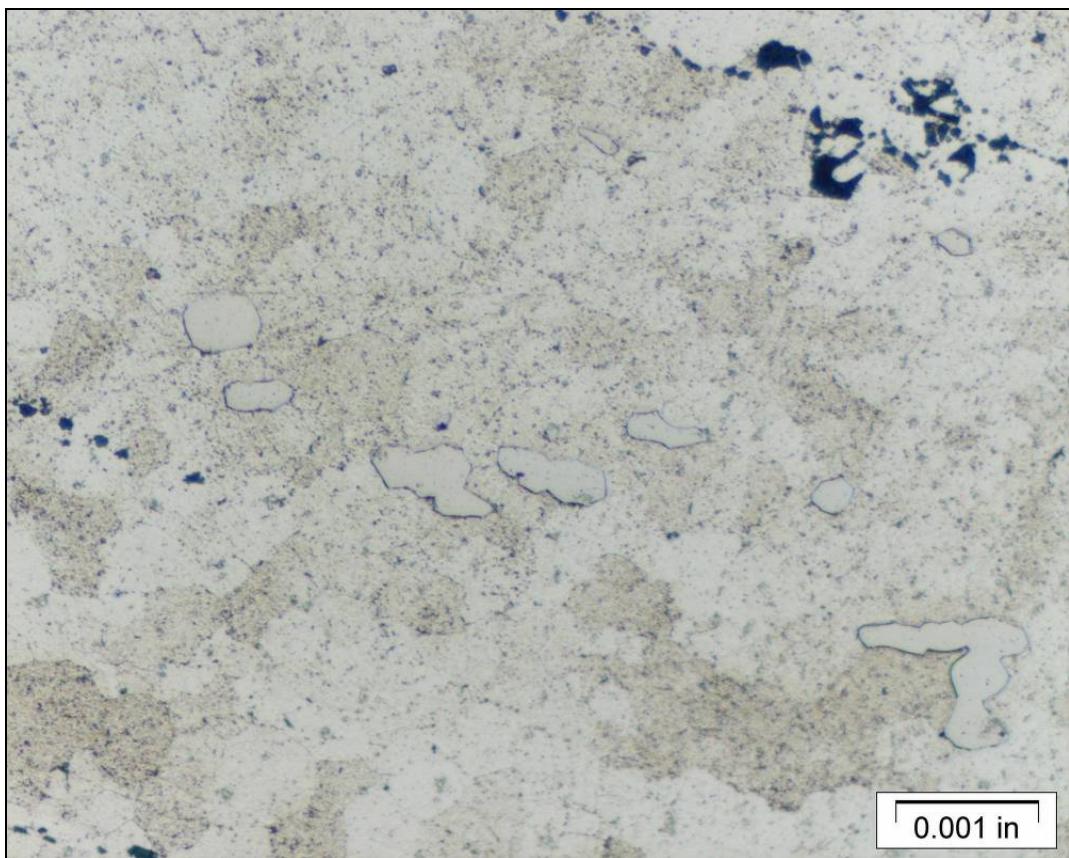


Figure 21. Typical microstructure of aluminum 2014-T6 base material.

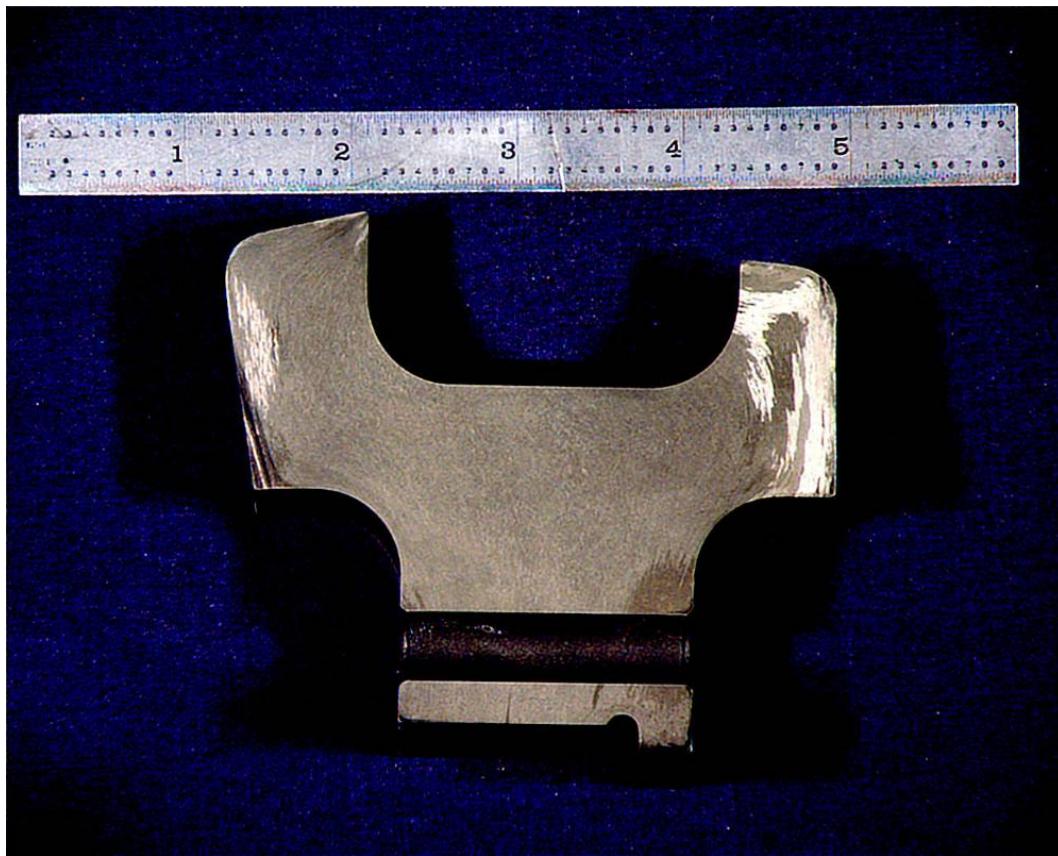


Figure 22. Macro-etch of a radial section depicting forging flow lines.

Table 1. Chemical composition of swashplate rotating rings by weight-percent.

Sample ID	BCW-1379 (%)	AMS-QQ-A-367 (%)
Iron	0.43	0.70 max
Manganese	0.70	0.40–1.20
Silicon	0.77	0.50–1.20
Copper	4.61	3.90–5.00
Zinc	0.17	0.25 max
Magnesium	0.48	0.20–0.80
Chromium	0.015	0.10 max
Titanium	0.028	0.15 max

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## 7. Hardness and Conductivity Testing

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Hardness and conductivity measurements were made near the cracked areas within the core of the rotating ring. The hardness of the component measured 82.3 Hardness Rockwell B-Scale (HRB) and the conductivity measured 38.5% International Annealed Copper Standard (IACS).

These values compared favorably with a 2014-T6 aluminum forging as specified by Boeing Aircraft Company (BAC) 5946 (78.5–89.5 HRB and 35%–40% IACS).

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## 8. Discussion

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There appear to be four types/causes of the cracking associated with the rotating rings:

1. Cracking associated with raised fretted areas from damage on the 16.19-in-diameter surface (numerous examples).
2. Cracking associated with pure fretting (hole 21 on S/N W1718240-1).
3. Cracking associated with extreme loads forming a network of cracks (hole 16 on S/N W1718240-1).
4. Cracking associated with uneven load distribution caused by the sharp chamfer of the outer bearing race (e.g., the circumferential crack on S/N BCW-1379).

The first seems easily rectified, and none have been observed to propagate radially. Nos. 2 and 3 appear to cause primarily radial cracks, while no. 4 appears to cause circumferential cracks.

The fractographic evidence, and the intuitively dominant hoop stresses on the component in service, suggest that circumferential cracks are slowly propagating and older than radial cracks (circumferential cracks are also more difficult to detect nondestructively). The number of circumferential cracks observed to date indicates they are a rare occurrence. The fracture surfaces of the horseshoe shaped cracks developing around raised areas caused from damage on the 16.19-in-diameter surface appear fresh and recent. These raised areas are most likely caused by damage incurred on the 16.19-in diameter during overhaul. The source of the damage to the 16.19-in diameter should easily be determined and rectified. To date, the horseshoe shaped cracks emanating around the raised areas have not resulted in spalling at the 16.19-in diameter. Cracks of this type have not been observed to turn radially and propagate into the part.

The rotating rings appear to have a wear pattern and crack concentration with 120° symmetry, with the areas between the pitch link locations possessing the greatest concentration of cracks and the most severe wear. This suggests that the assembly is deflecting considerably during service. This deflection is most likely not accounted for in the design and stress profile calculations of the rotating ring. In short, the assembly appears to be both overloaded and/or possess insufficient stiffness.

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## 9. Recommendations

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Elimination of the procedure and/or tool causing the damage on the 16.19-in-diameter surface seems prudent. This is most likely occurring at overhaul and is the most prominent cause of localized high stresses on the bearing retention shoulder of the rotating rings.

Although it is likely not the most common cause of local high stresses, it would seem that the surface finish and chamfer on the mating bearing should be scrutinized to determine if they detrimentally affect the rotating ring under contact and service loading.

Finally, the high degree of fretting observed in areas free of the damage discussed in the previous paragraphs suggests that the service loading of rotating rings may be excessive. The alleviation of high service loads or the use of a material with a greater endurance limit would likely increase the service life of the rotating ring. The use of a material with a greater modulus of elasticity might also be beneficial, but the resulting higher alternating stresses would have to be less than the endurance limit of the alternate material.

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## 10. Conclusions

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The subject swashplate rotating ring exhibited two cracks. Both cracks were located within the wear pattern observed on the bearing retention shoulder surface. One crack was located near hole 5 and oriented in the circumferential direction. The other crack was observed along the edge of a raised thumbnail shaped area near hole 30.

The circumferential crack was located approximately 0.015 in from the 16.19-in ID of the rotating ring and measured 0.35 in long  $\times$  0.090 in deep. The crack initiated by fatigue and high stress along a circumferential score line thought to be induced by the outer race of the mating swashplate bearing and subsequent contact (service and clamp-up) loads. The propagation in a nonradial direction, coupled with the oxidized fracture surface, suggested that this crack took longer to form than other cracks observed to date, on other rotating rings.

The crack along the edge of the raised thumbnail area initiated by fretting fatigue and localized high stresses. The localized high stresses were due to the reduced contact area the approximately 0.002-in high thumbnail area created. The raised area appeared to be a direct result of impact damage on the 16.19-in ID of the rotating ring from an unknown source, possibly at overhaul. The impact damage on the ID pushed material into the rotating ring, subsequently causing a bulge on the mating surface shoulder between the ring and the bearing.

Chemical, physical, and mechanical testing confirmed the rotating ring was forged from aluminum alloy 2014-T6 in accordance with drawing material requirements. The shot peening appeared uniform and consistent in all areas that were unaffected by wear.

No microstructural abnormalities were observed. The microstructure was consistent with an aluminum 2014-T6 alloy. Forging lines were observed generally following the contours of the component, confirming that the component was forged as required by the engineering drawing.

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ENGRG CMD  
SYSTEMS OF SYSTEMS  
INTEGRATION  
AMSRD SS T  
6000 6TH ST STE 100  
FORT BELVOIR VA 22060-5608

1 INST FOR ADVNCD TCHNLGY  
THE UNIV OF TEXAS  
AT AUSTIN  
3925 W BRAKER LN  
AUSTIN TX 78759-5316

1 DIRECTOR  
US ARMY RESEARCH LAB  
IMNE ALC IMS  
2800 POWDER MILL RD  
ADELPHI MD 20783-1197

3 DIRECTOR  
US ARMY RESEARCH LAB  
AMSRD ARL CI OK TL  
2800 POWDER MILL RD  
ADELPHI MD 20783-1197

ABERDEEN PROVING GROUND

1 DIR USARL  
AMSRD ARL CI OK TP (BLDG 4600)

NO. OF  
COPIES ORGANIZATION

ABERDEEN PROVING GROUND

2 DIR USARL  
AMSRD ARL WM MC  
S GRENDAHL

INTENTIONALLY LEFT BLANK.